Report on KC-135 Reduced Gravity Flights
for Flight Experiment Development of
the WONDER Payload (Flights: May 2002)

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Introduction

Two specific issues were to be addressed with reduced gravity tests on the KC-135 in Houston. The tests were to take place on May 5th, 6th and 7th. Successful tests were performed on May 5th and 6th, but mechanical problems with the KC-135 plane prevented flight on a third day. One item tested included a series of scaled down versions of the substrate modules designed for the PTIM as part of WONDER. These modules were flooded with dyed water to allow observation of fluid dynamics in zero gravity. Another test included the phase separation design incorporated into the PTIM. An air and water mixture was pumped into the phase separation device and the liquid output of the device was monitored for air bubbles. Each test was incorporated with a fixture provided by Texas A&M and a glovebox provided by Johnson Space Center (See Figure 1). This fixture is manifested to fly again in July, 2002. Additional WONDER tests may be performed on those flights.

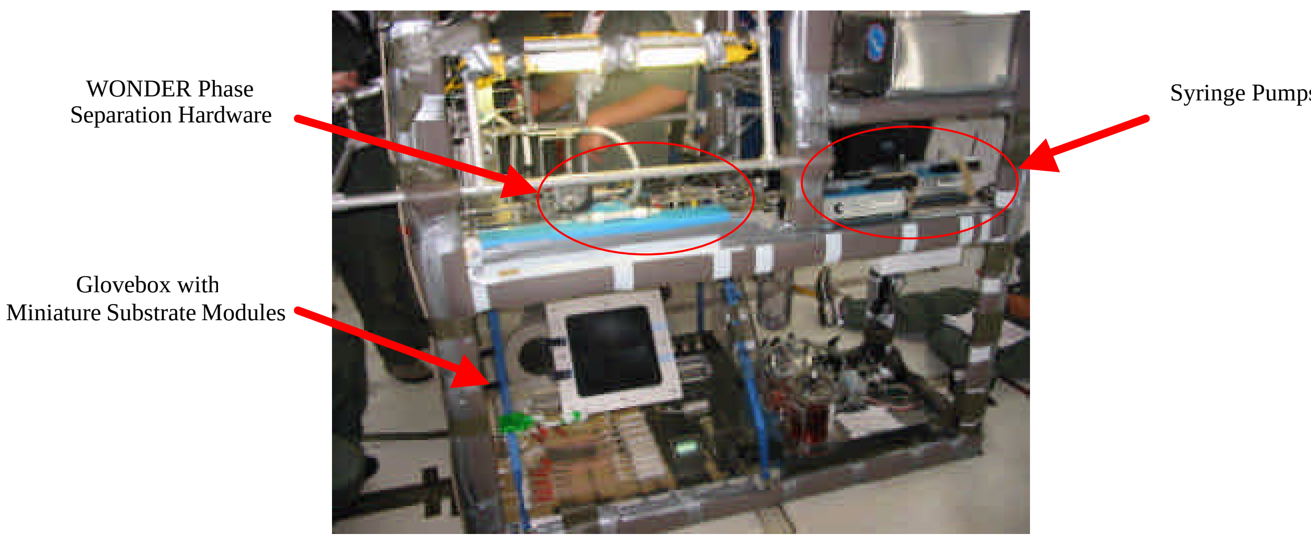


Figure 1 - Texas A&M Test Fixture with Glovebox and Phase Separation Hardware Installed

Video of KC-135 Setup:	KC-135 WONDER Setup.WMV

Scaled Down Substrate Module Test

Background

The PTIM flight hardware design includes 3 removable substrate modules (See Figure 2). These modules are filled with a substrate material (turface/arcillite) of 1-2 mm granular size. The modules are flooded with approximately 300 ml of solution through the use of a piston pump operating at a rate of 100 µl/sec. The water flows into the module through a porous tube which is in contact with a capillary mat. Seeds are glued to the top of the capillary mat and through capillary action, transfers water to the seeds. The module is constructed of aluminum sides and floor, perforated with venting holes. These surfaces are covered by a gas permeable PTFE/Polypropylene membrane (Mupor) to allow gas transfer but remain leak resistant. A perforated cover over the top of another sheet of Mupor is used to hold the substrate, capillary mat and plants in place.

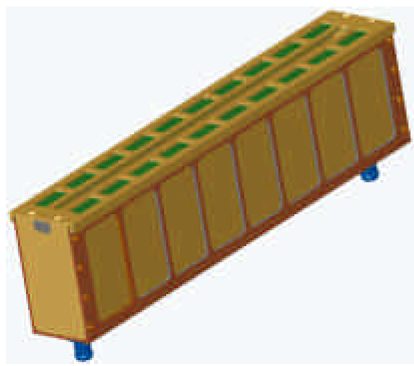


Figure 2 – Model of Full Scale PTIM Substrate Compartment. Notice Vents on Sides and Top.

Test Objectives

A concern regarding water escaping from the substrate module during fill was raised at the PTIM Critical Design Review. Because liquid flow characteristics differ in 0-g (versus 1-g) environment, the liquid injected into the module could possibly cling to and flow along the sides of the modules and escape out the top of the unit. The objective was to completely fill a substrate module at a rate more closely resembling the rate of the PTIM designed units (100 µL/sec). The fill was required to be accomplished in the 20 seconds of reduced gravity available at each parabola.

Hardware Design and Setup

A total of 10 miniature substrate modules were fabricated for this test. These modules were scaled down from the full size module design by a ratio of 3.2:1. The reason for the reduction in size was because of the requirement to fill the module within 20 seconds at a rate near 100 µl/sec (filling a full size module at 100 µl/sec takes approximately 50 minutes). The PTIM substrate module flight design includes a pump that injects at a maximum of 100 µl/sec per module. In order to fill the small scale versions within 20 seconds, the injection rate was required to be 470 µl/sec or above. This flow rate is still 4.7 times the rate incorporated in the PTIM design. The miniature modules were not made any smaller due to manufacture, cost, component availability and procedural issues.

At the bottom of each PTIM growth module is a porous tube used to evenly inject the liquid at the bottom of the module. The size of a scaled down porous tube was calculated at 0.125” outer diameter (OD). Porous tubes of this size are not available so a perforated tube design was used. Polyetheretherketone (PEEK) tubing (plastic) was perforated with 15 holes (axially) at each 90^o turn. Holes of 0.010” diameter were drilled in a staggered pattern to provide increased resistance to flow (and more uniform fluid excretion). The PTIM capillary mats were simulated with 1/3 thickness absorbent paper. The mats were wrapped around the tube and held in place by the top cover as in the full scale units. Capillary mats were not used in modules filled with glass beads or with unfilled modules.

The base, walls and cover of the modules were fabricated from optically clear acrylic. This provided visual feedback of fluid dynamics. The top cover was perforated to allow air to flow through the cover and into the substrate (as in the full size units). A Mupor (Teflon/Polypropylene) membrane was installed beneath the cover to prevent liquid from escaping the module (as in the full size units).

Since the full size PTIM modules include perforations on the sidewalls and floor covered with a Mupor lining, four of the units were modified to further simulate this design. On these four units all but the end walls were covered by Mupor, visually concealing the fluid flow. The mesh polypropylene side of the membrane was installed outward on 3 of these 4 units. The single indicator of fluid dynamics issues was the monitoring of the top cover for leakage during fill. Of the six units that did not have perforated walls or floor, one unit was lined with Mupor (polypropylene side out) to test any affects of the perforations on fluid flow.

A variety of fills were used for the testing. To simulate scaled down substrate material, turface was sieved down to three separate particle sizes. The full size PTIM modules incorporate 1 to 2 mm Turface. For this test, the following particle ranges were used: 0.25 to 0.50 mm, 0.5 to 1.0 mm, 1 to 2 mm

The modules were tested with a leak resistant glovebox designed and built by JSC (See Figure 3, Glovebox POC: David Treat). The glovebox was mounted to a fixture built by Texas A&M specifically for KC-135 use (POC: Cable Kurwitz). Each module was equipped with a syringe and tubing leading to the perforated tube. The syringes were filled with a predetermined volume of red dyed water to inject into the units. An 8 mm video camera was situated inside the glovebox for video capture. In front of the camera, a small stand was mounted to the glovebox floor. This stand properly positioned the units in the camera’s view. Three vials of desiccant particles were fixed to the backing of the stand. These vials provided visual indications of basic vertical acceleration levels and were recorded by the video camera.

Figure 3 – Glovebox with miniature substrate modules and camera inside

Figure 4 – Miniature Substrate Module with Optically Clear Walls (5 units fabricated)

Figure 5 – Miniature Substrate Module with Optically Clear Walls and Mupor Lining (1 unit fabricated)

Figure 6 – Miniature Substrate Module with Perforated, Mupor Lined Walls (4 units fabricated)

Test Setup and Protocol

<u>Ground Test Results (1g)</u>

All injections occurred on the ground (1 g)

Module	Vents	Membrane	Cap. Mat	Fill	Fill Volume	Estimated Fill Rate	Fluid Flow Observ.	Visible Dust?	Video Clip
1	Yes	Polypro side in	Yes	0.5 to 1 mm Turface	11 mL	700 µl/sec	No leaks	No	Ground_Module1.WMV
2	Yes	Polypro side out	Yes	0.25 to 0.5 mm Turface	11 mL	900 µl/sec	No leaks until overfilled	No	Ground_Module2.WMV
3	Yes	Polypro side out	Yes	0.5 to 1 mm Turface	11 mL	700 µl/sec	No leaks	No	Ground_Module3.WMV
4	Yes	Polypro side out	Yes	1 to 2 mm Turface	11 mL	1000 µl/sec	No leaks.	No	Ground_Module4.WMV
5	No	Polypro side out	Yes	1 to 2 mm Turface	11 mL	800 µl/sec	No leaks.	Minimal	Ground_Module5.WMV
6	No	None	No	None (empty)	14 mL	1000 µl/sec	Uniform. No leaks until overfilled.	N/A	Ground_Module6.WMV
7	No	None	No	None (empty)	14 mL	1100 µl/sec	Uniform. No leaks until overfilled.	N/A	Ground_Module7.WMV

8	No	None	No	1 to 2 mm Glass Beads	7 mL	500 µl/sec	Uniform. No leaks until overfilled.	N/A	Ground_Module8.WMV
9	No	None	**No**	1 to 2 mm Glass Beads	7 mL	600 µl/sec	Uniform. No leaks until overfilled.	N/A	Ground_Module9.WMV
10	No	None	Yes	1 to 2 mm Turface	11 mL	800 µl/sec	Uniform. No leaks.	Minimal	Ground_Module10.WMV

<u>Flight Day 1 Setup and Results:</u>

All injections occurred in the 0-g periods of flight

Module	**Vents**	**Membrane**	**Cap. Mat**	**Fill**	**Fill Volume**	**Estimated Fill Rate**	**Fluid Flow Observ.**	**Visible Dust?**	**Video Clip**
1	Yes	Polypro side in	Yes	0.5 to 1 mm Turface	9 ml	900 µl/sec	Uniform with no Leaks	Minimal	Day1_Module1.WMV
2	Yes	Polypro side out	Yes	0.25 to 0.5 mm Turface	9 ml	900 µl/sec	Leaked out End of unsealed tube	N/A	Day1_Module2A.WMV
3	Yes	Polypro side out	Yes	0.5 to 1 mm Turface	9 ml	800 µl/sec	Uniform with no Leaks	Yes	Day1_Module3A.WMV
4	Yes	Polypro side out	Yes	1 to 2 mm Turface	9 ml	800 µl/sec	Uniform with no Leaks	Yes	Day1_Module4A.WMV

5	No	Polypro side out	Yes	1 to 2 mm Turface	9 ml	900 μl/sec	Uniform with no Leaks	Yes	Day1_Module5A.WMV
6	No	None	No	None (empty)	13 ml	1000 μl/sec	Uniform with no Leaks	N/A	Day1_Module6.WMV
7	No	None	No	1 to 2 mm Glass Beads	6 ml	600 μl/sec	Leaked out End of unsealed tube	N/A	Day1_Module7.WMV
8	No	None	Yes	0.25 to 0.5 mm Turface	9 ml	900 μl/sec	Uniform with no Leaks	No	Day1_Module8.WMV
9	No	None	Yes	0.5 to 1 mm Turface	9 ml	N/A	Leaked out End of unsealed tube	N/A	Day1_Module9.WMV
10	No	None	Yes	1 to 2 mm Turface	9 ml	900 μl/sec	Uniform with no Leaks	Yes	Day1_Module10.WMV

<u>Flight Day 2 Setup and Results:</u>

All injections occurred in the 0-g periods of flight

Module	**Vents**	**Membrane**	**Cap. Mat**	**Fill**	**Fill Volume**	**Estimated Fill Rate**	**Fluid Flow Observ.**	**Visible Dust?**	**Video Clip**
1	Yes	Polypro side in	Yes	0.5 to 1 mm Turface	**10 mL**	N/A	Problem w/fluid injection	N/A	Day2_Module1.WMV
2	Yes	Polypro side out	Yes	0.25 to 0.5 mm Turface	**10 mL**	1300 ul/sec	No leaks	No.	Day2_Module2A.WMV

3	Yes	Polypro side out	Yes	0.5 to 1 mm Turface	**10 mL**	1600 µl/sec	No leaks.	Yes	Day2_Module3A.WMV
4	Yes	Polypro side out	Yes	1 to 2 mm Turface	**10 mL**	1600 µl/sec	No leaks.	Yes	Day2_Module4A.WMV
5	No	Polypro side out	Yes	1 to 2 mm Turface	**10 mL**	900 µl/sec	No leaks.	Yes.	Day2_Module5A.WMV
6	No	None	No	None (empty)	**14 mL**	1600 µl/sec	Uniform Injection. No leaks until it was overfill. High flow rate produced streams of water coming out holes in tube. Liquid climbed walls.	N/A	Day2_Module6A.WMV
7	No	None	No	1 to 2 mm Glass Beads	**7 mL**	900 µl/sec	Uniform Injection. No leaks until it was overfilled.	N/A	Day2_Module7A.WMV
8	No	None	**No**	**1 to 2 mm Glass Beads**	**7 mL**	1400 µl/sec	Uniform Injection. No leaks until it was overfilled.	N/A	Day2_Module8A.WMV

9	No	None	Yes	0.5 to 1 mm Turface	**10 mL**	1100 µl/sec	No leaks.	Some	Day2_Module9A.WMV
10	No	None	Yes	1 to 2 mm Turface	**10 mL**	1100 µl/sec	Water was somewhat uneven (more at ends of module). No leaks.	Yes. Lots.	Day2_Module10A.WMV

(Note: Changes from Day 1 are in Bold)

Observations of Results

Fluid Flow

As long as the modules were not overfilled, they did not leak. If a module was overfilled, liquid would most likely escape at the ends of the unit (beneath the cover). Liquid did not escape through the top slit of the unit. Although liquid did flow up the corner of some modules (evidenced on modules 9 and 10, flight day 2) the liquid eventually became evenly distributed and was contained within the modules. Test of module 6 on flight day 2 (empty module) showed that the fluid did tend to migrate toward the corners of the unit and flow up the edges. Again in this case, the unit did not leak until it was overfilled with liquid. On day 1, module 6 was injected more slowly (1000 µl/sec versus 1600 µl/sec). The slower injection seemed to help distribute the flow of liquid and inhibit the liquid from "climbing" the walls so quickly.

Substrate "Dust"

A more visible amount of dust could be seen in the reduced gravity injections as opposed to the 1-g ground control tests. One theory is that in reduced gravity the dust is more loosely held in place, thus when the water level begins to rise, the displaced air pushes out the dust through the top cover. Dust seemed to be propelled more readily through turface with larger sieve size (1-2 mm) than the smaller sized turface. This may be because of the larger spacing between particles, allowing a less restrictive path for air (and dust) to flow through the substrate.

In the full size substrate units, the liquid level rises as a much slower rate than in the small units. The surface of the liquid in the full size modules will rise at a rate of approximately 0.02 mm/sec. The surface of the liquid in the miniature modules was propelled at a rate of approximately 1.8 mm/sec, which is 90x the rate of the full size modules. This fast rate of air displacement may have caused the dust to be "stirred up" and sent out into the air above the unit.

Test Setup and Performance Issues

On flight day 1, the seals on the downstream end of the tubes of modules 2, 7 and 8 were damaged. This caused fluid to leak out unexpectedly. The units were repaired for the second flight day. This was an issue relating to the miniature substrate units only (not the full size units). On flight day 2, the inlet valve for module 1 was not opened prior to the injection attempt (preflight procedural error). Thus, the unit was not properly filled.

Note

The ground testing of these modules was performed on what would have been “Flight Day 3”. Testing was performed in the Hanger at Ellington Field, Houston, TX.

Phase Separation (Bubble Trap) Test

Background

Since the PTIM porous tubes are not fully submerged in liquid, if liquid is removed from the growth modules, air bubbles may be introduced into the liquid stream. To ensure the liquid reservoir does not fill with air, a liquid/gas separator has been incorporated into the PTIM. The main separation device is a membrane contactor containing 1100 bundled hydrophobic hollow porous fibers. The bundle is enclosed in a sealed casing. The air pressure in the casing is maintained at 13.8 kPa to 20.7 kPa (2 to 3 psi) below ambient pressure by a miniature air/vacuum pump, solenoid valve and microcontroller. This negative pressure pulls the bubbles out of solution while allowing the liquid to continue flowing through the fibers and to the reservoir. The condensate returned by the Plant Generic Bioprocessing Apparatus (PGBA: WONDER environmental chamber) dehumidifier will also pass through the separator prior to reaching the reservoir.

Test Objectives

This series of KC-135 flights was to prove acceptable operation of the PTIM phase separation system in a reduced gravity environment.

Hardware Design and Setup

A pressure control system was constructed using a PIC microcontroller, Omega +/- 5 psid pressure sensor, Gast miniature air pump, LEE check valve and LEE miniature solenoid valve. These are the same components intended for the PTIM flight units. The microcontroller reads the voltage from the pressure sensor and controls operation of the pump and valve depending on the set points. The check valve holds the vacuum within the membrane contactor so the air pump is not required to run continuously.

The microcontroller was programmed to remove air from the membrane contactor casing until the pressure level is below –2 psid. If the ambient pressure begins to rise (while the pressure in the contactor remains constant), and the differential pressure between the ambient and the membrane contactor drops below –3.15 psid, the microcontroller opens a solenoid valve, which decreases the differential pressure. The solenoid valve is closed when the differential pressure is greater than –2.5 psid.

The pump, valves and microcontroller board were enclosed within an aluminum case. The case was fitted with quick disconnects. Tubing from the quick disconnects was routed to the air ports of the membrane contactor. The membrane contactor was horizontally mounted on the TA&M rack (See Figure 5). Two syringe pumps were used to independently push air and water into tubing leading to the membrane contactor. This mixture resulted in slug flow of air bubbles. The liquid outlet of the membrane contactor was routed to a sealed reservoir with a vent valve. The vent valve was to be opened at least every 10 parabolas to prevent pressure build-up within the reservoir (at the contactor outlet).

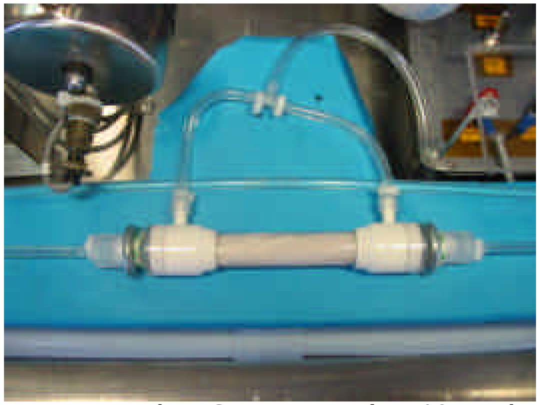


Figure 5 – Membrane Contactor Mounted on TA&M Rack

The syringe pumps were fitted with 45 ml syringes. Since one 45 ml syringe would last less than 10 parabolas, additional syringes filled with water were held in a storage drawer on the rack. An additional pressure sensor was fitted onto the system at the phase mixture point. This sensor was provided by TA&M.

Power (5V DC and 12V DC) was supplied to the pressure controller by the TA&M rack. The 12V power supply was current limited when a pump from another experiment on the rack was in use. This prevented the pressure controller from operating correctly during those periods. Fortunately, those periods of operation were to occur at the 1g level flight turnaround points.

The analog output voltage from the pressure (vacuum) and the pressure sensor output at the mixture point were tied into the TA&M data logging system. This data was time correlated with 3-axis acceleration, ambient pressure and ambient temperature. A video camera was mounted above the membrane contactor to record inlet and outlet observations.

Test Setup and Protocol

Prior to takeoff, the membrane contactor was positioned on end with the liquid outlet facing upward. The pressure controller was turned on and approximately 300 mL of water was pushed through the contactor while tapping on it to remove any trapped air. The membrane contactor was then situated horizontally.

This test was set up to operate with minimal interaction. The pressure controller was powered on followed by the two syringe pumps. The air and water mixed together at a fluid junction and was pushed into the membrane contactor. The pressure controller would autonomously maintain the vacuum inside the contactor casing. Once the syringes were expended, the air syringe was reloaded (plunger turned back) and the water syringe was replaced with a fully loaded syringe.

Day 1 Protocol and Observations (Fliers: Levine/Burtness)

Parabolas	Action	Observations
1 through 5	Loss of Power to Pumps and Controller	No Air or Water Flow Through Contactor
6 through 10	3.5 ml/min air injection + 3.5 ml/min water injection	No Air Passed Through Contactor
Turnaround through 11	Replaced Injection Syringes	N/A (No flow)
12 through 20	3.5 ml/min air injection + 3.5 ml/min water injection	No Air Passed Through Contactor
Turnaround	Replaced Syringes	N/A (No flow)
21 through 27	4.3 ml/min air injection + 4.3 ml/min water injection	Small (1mm) Bubble Past Contactor
28 through Turnaround	Replaced Syringes	N/A (No flow)
31 through 37	4.3 ml/min air injection + 4.3 ml/min water injection	No More Air Passed Through Contactor
38 through 40	Test Complete	No Flow (Complete With Test)

Day 2 Protocol and Observations (Fliers: Levine/Norikane)

Parabolas	Action	Observations
Level Flight through 3	3.5 ml/min air injection + 3.5 ml/min water injection	Bubble at Contactor Exit at Start of Experiment
4 through Turnaround	Replaced Syringes	N/A (No flow)
11 through 19	3.5 ml/min air injection + 3.5 ml/min water injection	Bubble still at Contactor Exit. No additional.
20 through Turnaround	Replaced Syringes	N/A (No flow)
21 through 28	4.3 ml/min air injection + 4.3 ml/min water injection	Bubble still at Contactor Exit. No additional.
29 through Turnaround	Replaced Syringes	N/A (No flow)
31 through 35	8.4 ml/min air injection + 8.4 ml/min water injection	Bubble still at Contactor Exit. No additional.
36 through 40	Test Complete	No Flow (Complete With Test)

Observations of Results

Across both days, a total of approximately 350 mL of air plus 350 mL of water was pumped through the membrane contactor. On day one, a small (max of 0.2 ml volume) air bubble was noticed at the membrane contactor exit near the halfway point of flight. On day two, a small (max 0.2 ml volume) air bubble was noticed at the membrane contactor exit prior to flight. This small bubble could have been air that escaped past the device while in operation or during preflight (powered down) operations. In either case, this was the only air seen at the outlet of the membrane contactor throughout all KC-135 tests. The air and water flow of the test ranged from a combined 7 mL/min to 16.8 mL/min. Over the test, the phase separator removed over 99.9% of air from solution.

Pressure (vacuum control results)

Figure 6 and 7 show the three acceleration components (x/y/z) and the vacuum pressure inside the contactor for the two flight days. The pressure inside the contactor is shown in both units of psid and psig.

In figure 6 the differential pressure (pressure difference between inside contactor and ambient pressure) was controlled well by the microcontroller/pressure sensing system (same as in PTIM design). In figure 7, the differential pressure was properly maintained until it began to rise toward ambient pressure just after parabola 33. This occurred because the vacuum controller lost 12V power for 56 seconds. Thus the air being pumped into the contactor (as part of the mixture) raised the pressure inside the contactor. Once power was restored, pressure was adequately maintained. The 12V power was lost due to a current limited power supply being used by more than one experiment on the test fixture.

On day 1 (figure 6), forty parabolas can be recognized. Between each set of 10 parabolas was a turn around period (1g), but during this time data was not recorded so those points are not seen on the graph.

Figure 8 and 9 show the measured pressure data sets on one chart (all in psig). Inlet pressure is the pressure of the air/water mixture going into the membrane contactor. It fluctuated based on cabin pressure fluctuations and because of pressure buildup and release within the reservoir. On day 2, this inlet pressure rose to above 2 psig. This is because of a buildup of pressure inside the collection reservoir. The pressure release valve remained closed from takeoff until parabola 8. Once the plane was in flight, the cabin pressure dropped about 2 psi but the pressure inside the collection reservoir was maintained, resulting in a differential pressure near 2 psi.

The ambient pressure (see figures 8 and 9) show the KC-135 ambient pressure (in gauge). This pressure fluctuates based on the parabola profile, primarily due to changes in altitude. Figures 8 and 9 also show the gauge pressure in the membrane contactor. As you can see, this pressure fluctuates with ambient pressure, but maintains adequate differential pressure.

Figure 6: Day 1 Membrane Contactor Inlet Pressure and Gz, Gx, Gy versus Time (in Seconds)

(Parabolas 1 - 40 Shown)

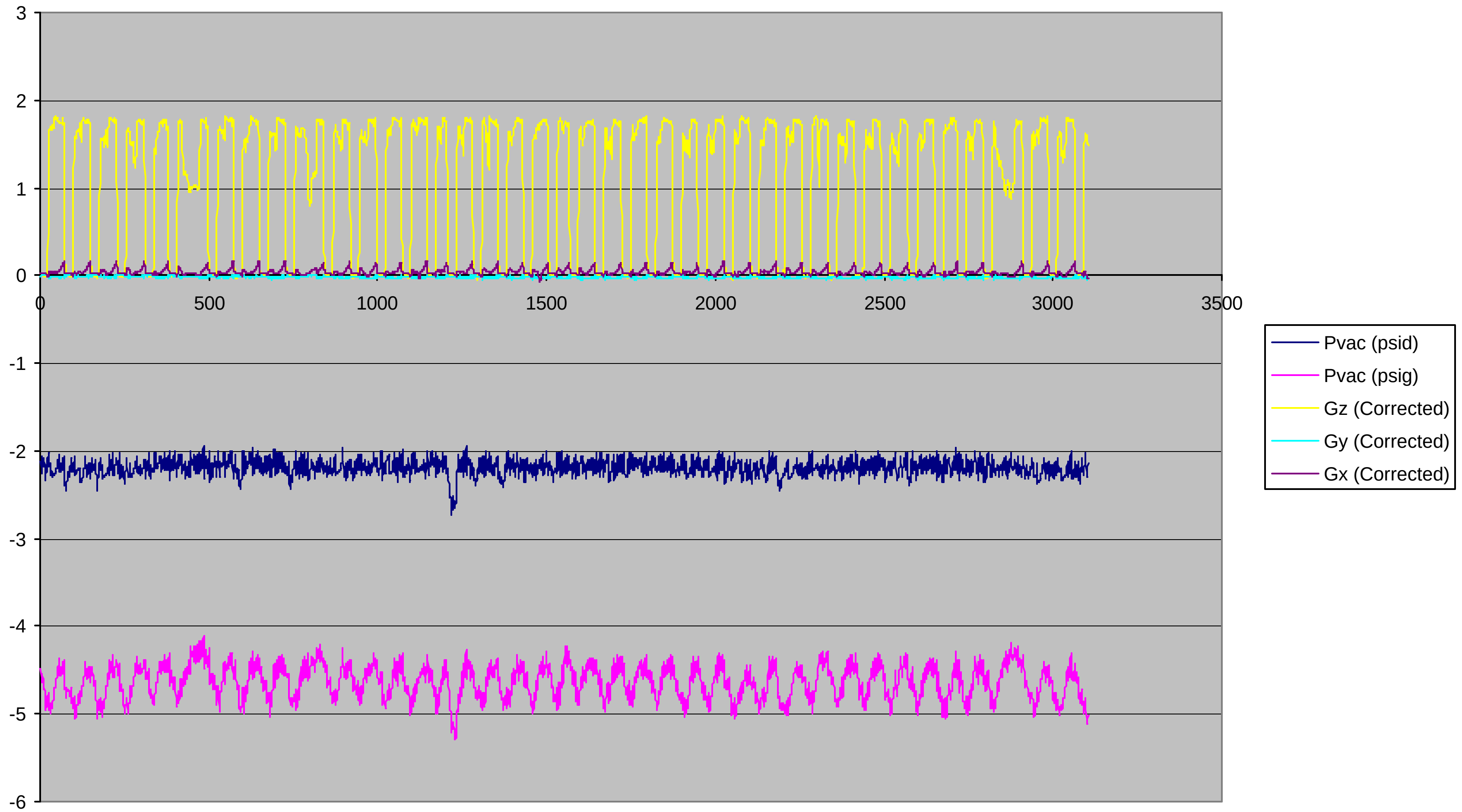


Figure 7: Day 2 Membrane Contactor Inlet Pressure and Gz, Gx, Gy versus Time (in Seconds)

(Parabolas 1 - 40 Shown)

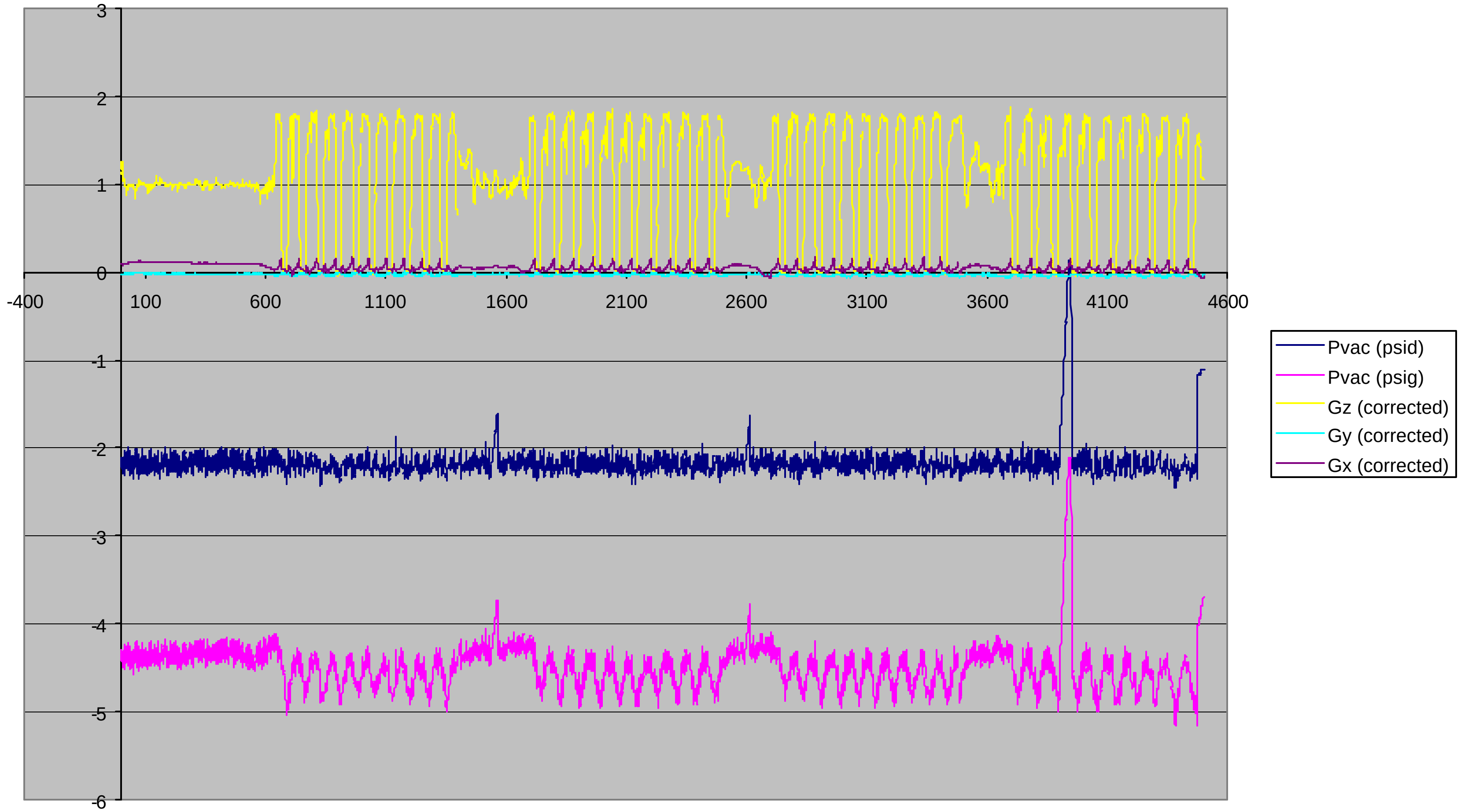


Figure 8: Day 1 Pressure Data versus Time (in Seconds)

(Parabolas 1 - 40 Shown)

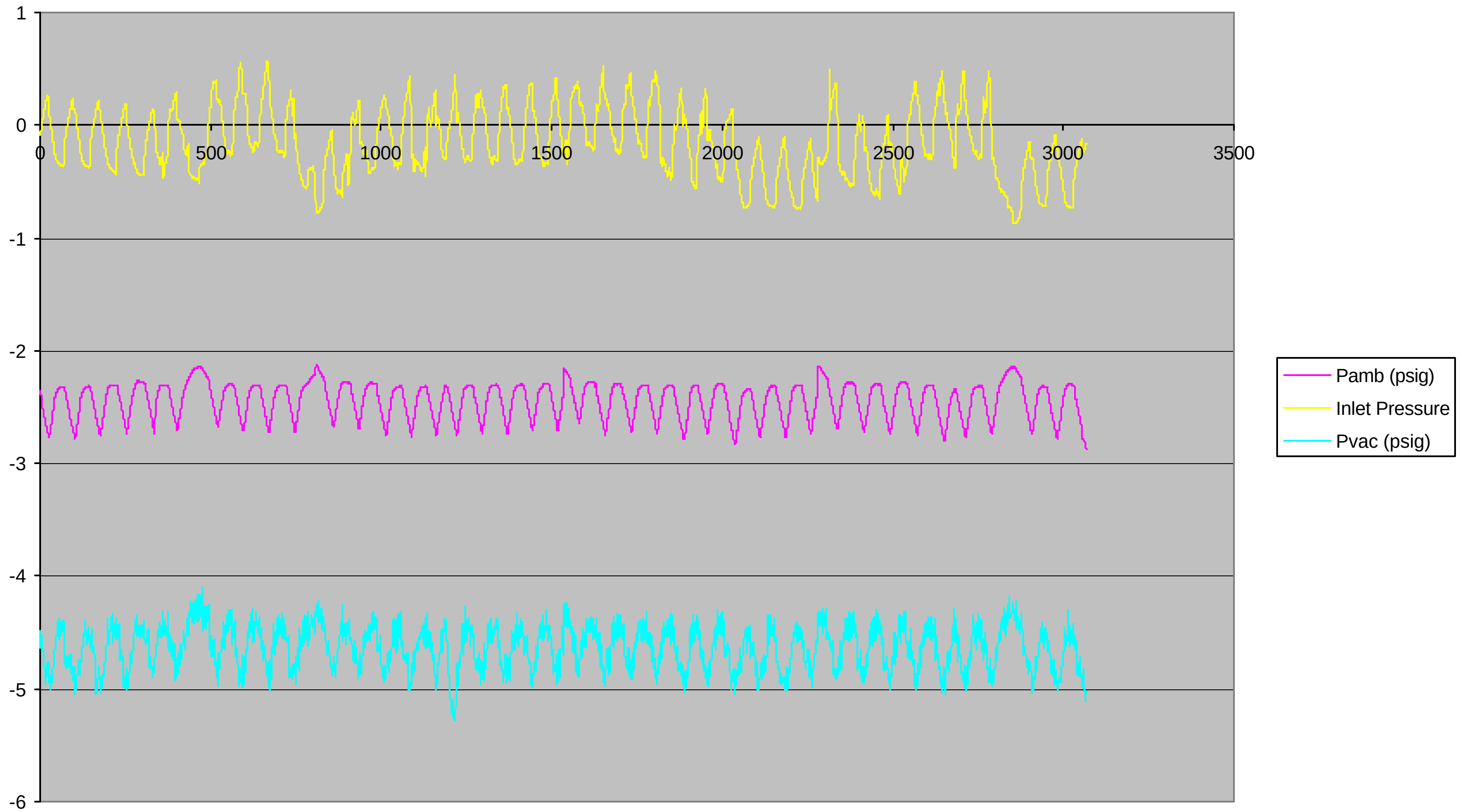
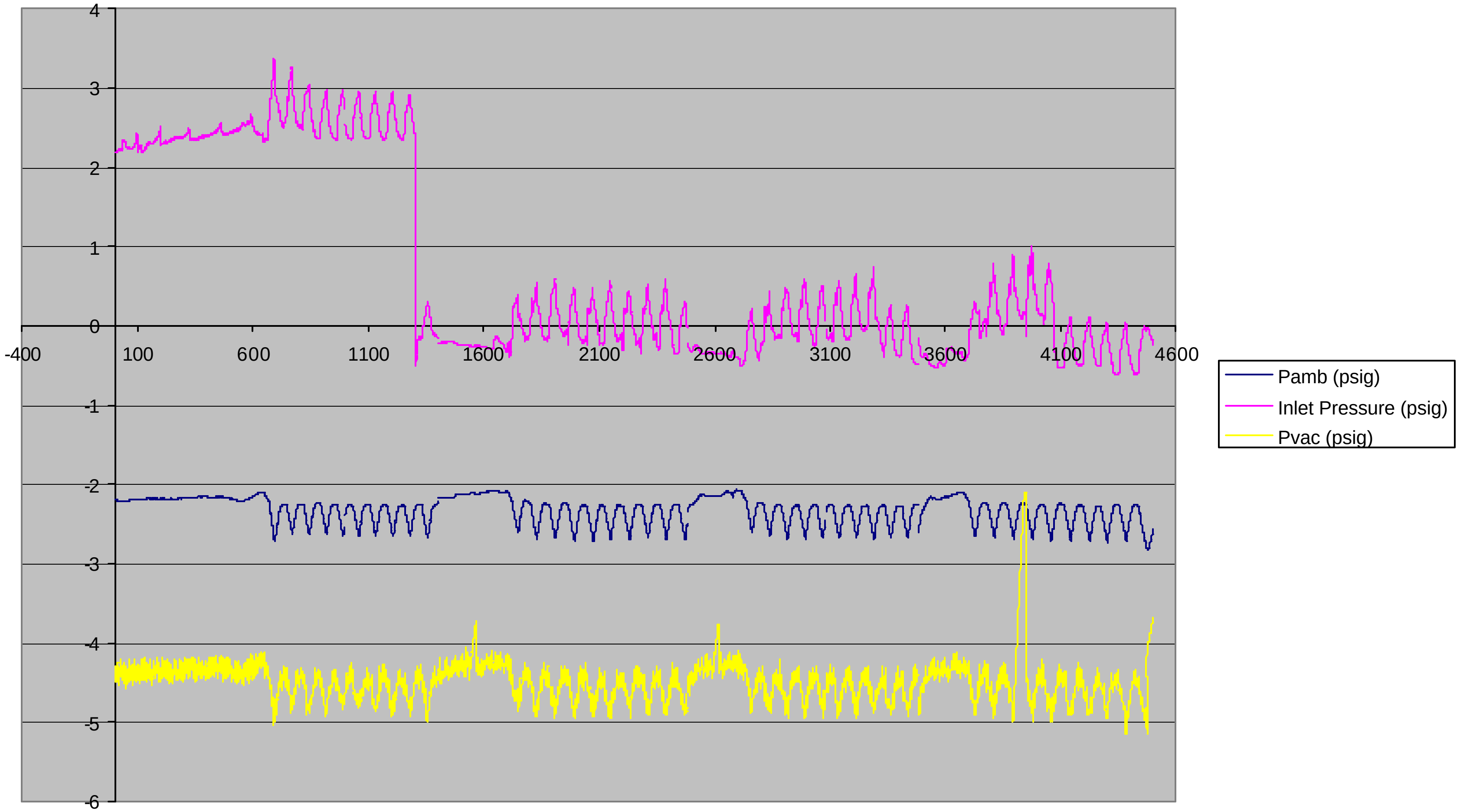


Figure 9: Day 2 Pressure Data versus Time (in Seconds)

(Parabolas 1 - 40 Shown)



Syringe Pump Calibration Data

Setting 6

	Pump 1			Pump 2		
	Time [min]	Volume [ml]	Flow Rate [ml/min]	Time [min]	Volume [ml]	Flow Rate [ml/min]
	3	5	1.67	3	8	2.67
	4	9.5	2.38	4	10	2.50
	3	7.5	2.50	3	8	2.67
	4	9.5	2.38	4	10	2.50
Average			2.23			2.58

~2.41 l/min for both syringe pumps

Setting 7

	Pump 1			Pump 2		
	Time [min]	Volume [ml]	Flow Rate [ml/min]	Time [min]	Volume [ml]	Flow Rate [ml/min]
	3	9	3.00	3	11	3.67
	4	15	3.75	4	14	3.50
	3	11	3.67	3	10	3.33
	4	14	3.50	4	14	3.50
Average			3.48			3.50

~3.49 l/min for both syringe pumps

Setting 8

	Pump 1			Pump 2		
	Time [min]	Volume [ml]	Flow Rate [ml/min]	Time [min]	Volume [ml]	Flow Rate [ml/min]
	3	10	3.33	3	11	3.67
	4	20.5	5.13	4	20	5.00
	3	10.5	3.50	3	10.5	3.50
	4	20.5	5.13	4	21	5.25
Average			4.27			4.35

~4.31 l/min for both syringe pumps

Setting 9

	Pump 1			Pump 2		
	Time [min]	Volume [ml]	Flow Rate [ml/min]	Time [min]	Volume [ml]	Flow Rate [ml/min]
	3	25.5	8.50	3	25	8.33
	4	34	8.50	4	34	8.50
	3	26	8.67	3	25	8.33
	4	34	8.50	4	33.5	8.38
Average			8.54			8.39

~8.47 l/min for both syringe pumps